

9th Eco-Energy and Materials Science and Engineering Symposium

Micro Stirling Engine Controlled by Light

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Abstract

This paper proposes a new technique for a micro Stirling engine operation using leaky light resonant or whispering gallery modes (WGMs) in a nano-waveguide, in which the nano-waveguide is designed and configured by a nanoring resonator. By using the Optiwave programming based on Finite Difference Time-Domain (FDTD) method, an *InGaAsP/InP* nanoring resonator was designed and simulated. The simulation results obtained have shown that the leaky light resonant modes can be controlled by the ring radius variations, whereas the maximum resonant peak of nanoring resonator is occurred at the inner and outer ring radii of 0.775 and 1.55 μm respectively. The maximum peak intensity of the nanoring resonator is 12000 W/m^2 . Finally, the use of leaky light mode resonant peak of the center nanoring resonator for micro-Stirling engine is discussed in details.

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Keywords: Leaky light mode; Whispering gallery mode; Nanoring resonator; Stirling engine; Micro engine

1. Introduction

Now we introduce the new devices known as a “ring resonator” which is in the circular form or planar waveguide which was introduced by Yupapin et al. [1, 2]. The ring resonator was used to the solar energy conversion [3] and this paper the ring resonator was used to convert the leaky light intensity into thermal energy. We call the leaky light mode or whispering gallery mode (WGMs). The study of WGMs was started almost a century ago with the work of Lord Rayleigh, who studied propagation of sound over a curved gallery surface [4–6]. The first observation of WGMs in optics can be attributed to solid-state WGM lasers. Laser action was studied in Sm: CaF_2 crystalline resonators [7]. The size of the resonators was in the millimeter range. Pulsed laser operation due to complete internal reflection in a ruby ring at room temperature has been observed [8]. Short-lived transient oscillations rather than spikes in the laser

output were explained by assuming a WGM Q of 108 to 109. In liquid resonators, WGMs were first observed by elastic light scattering from spherical dielectric particles [9, 10]. It was recognized that WGMs could help in measurements of spherical particle size, shape, refractive index, and temperature [11, 12]. WGMs were used to determine the diameter of the optical fiber [13]. The strong influence of WGMs on fluorescence and Raman scattering was recognized in [14–16] and [17–19], respectively. Laser action in a droplet was first studied in [20, 21].

Recent technological advances in micro-and nano-photonics have boosted the realization and testing of extremely high Q-factor optical resonator systems. Much interest is focused on two dimensional whispering-gallery mode (WGM) resonators [22, 23], such as micro-disks [24], rings [25] and toroids [26]; these are chip-integrable and offer a wide spectrum of possible applications ranging from microdisk (m-disk) lasers [27, 28] to sensing [29]. In this paper, the whispering gallery modes were controlled by varies radius of nano-ring resonator, which may be suitable for small heat source applications.

2. Leaky Light Mode in a Ring Resonator

Light propagating in a straight waveguide is confined via total internal reflection (TIR) by two dielectric interfaces (along one dimension) to a region of high refractive index. Light propagating in a curved waveguide is still guided via TIR at the outer interface, but no longer demands an inner interface to complete the confinement. Elimination of the inner boundary leaves a dielectric disk or ring which supports whispering gallery modes. These modes consist of azimuthally propagating fields guided by TIR at the dielectric interface and optical inertia which prevents the field from penetrating inward beyond a fixed radius. Mathematically, a whispering gallery mode is a solution of the Helmholtz equation in a curved coordinate geometry. Attention is restricted to a cylindrical geometry appropriate for the analysis of planar disk and ring resonators. The Helmholtz equation ($\nabla^2 + k^2$) $E_z = 0$, written in cylindrical coordinates the whispering gallery modes is [30]

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \varphi^2} + k^2 \right) E_z(r, \varphi) = 0 \quad (1)$$

Where r is the radial distance, φ is the angle measured counterclockwise from the polar axis to the ray from the origin.

The equation can be the method of separation of variable by which it is split into two equations for radial and azimuthally dependence. An integer parameter m is introduced which connect the two equations and physically correspond to the number of optical cycles the field under goes when completing one revolution around the ring. The azimuthally equation takes the form

$$\left(\frac{\partial^2}{\partial \varphi^2} + m^2 \right) E_z(\varphi) = 0 \quad (2)$$

and has solution are complex exponentials,

$$E_z(\varphi) = e^{\pm im\varphi}$$

The radial equation is the Bessel's function

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + k^2 - \frac{m^2}{r^2} \right) E_z(r) = 0 \quad (3)$$

Solutions of Bessel's equation are the Bessel's function of the first J_m and the second Y_m kind. Because the second kind function is singular at the origin, only the first kind function is retained inside the ring. Outside the ring both functions are well behave and must be retained. The Hankel functions are linear superposition of two Bessel function solutions corresponding to outward, $H_m^{(1)} = J_m + iY_m$ and inward

$H_m^{(2)} = J_m - iY_m$ propagating cylindrical waves. The analysis of wave arriving at the resonator from

the radial horizon is not considers here and thus only the Hankel function of the first kind, $H_m^{(1)}$ is retained. Thus, the appropriate solution for the radial field dependence both interior ($r < R$) and exterior ($r > R$) to the dielectric ring are

$$E_z(r < R) = A_m J_m(\tilde{k}_1 r) \quad (4)$$

$$E_z(r > R) = B_m H_m^{(1)}(\tilde{k}_2 r) \quad (5)$$

Here $\tilde{k}_j$ is complex propagation constant

The complete axial electric field interior and exterior to the ring is constructed from the azimuthal and radial solutions including the boundary condition at the interface ($r = R$) which forces the tangential electric field to be continuous:

$$E_z(r, \varphi) = A_m J_m(\tilde{k}_1 r) e^{i(\pm m \varphi - \tilde{\omega} t)} \quad (6)$$

$$E_z(r, \varphi) = A_m \frac{J_m(\tilde{k}_1 R)}{H_m^{(1)}(\tilde{k}_2 R)} H_m^{(1)}(\tilde{k}_2 r) e^{i(\pm m \varphi - \tilde{\omega} t)} \quad (7)$$

3. Micro Stirling Engine Concept

The integrated optical device material used is InGaAsP/InP, in which the refractive index of material is 3.34, while the cladding of material is air, with the light source center wavelength is at 1.55 μm , the peak power laser input of 10 W which was launched into the system (a nanoring resonator). The device is double ring as shown in Figure 1. The double ring radii were varied by (i) inner ring radius from 0.60 μm to 0.95 μm and (ii) the outer ring radius was fixed at 1.55 μm . The width of resonator was 0.3 μm . All design and simulation results were obtained by using the Optiwave programming. In this simulation, the leaky light mode outside the rings is neglected, while inside ones can be formed the WGMs resonant peak at the ring center. By varying the inner ring radius, the double ring resonator can also be formed the leaky light mode peak intensity. The intensity will be increased and sharpened. The double ring resonator with outer ring radius of 1.55 μm and inner ring radius of 0.775 μm give the maximum leaky light mode peak intensity. The 3-D plot of the peak intensity is as shown in Fig. 2. Results obtained have shown that the highest center peak intensity of the double nanoring can be useful for micro-Stirling engine, which is shown in Fig.3.

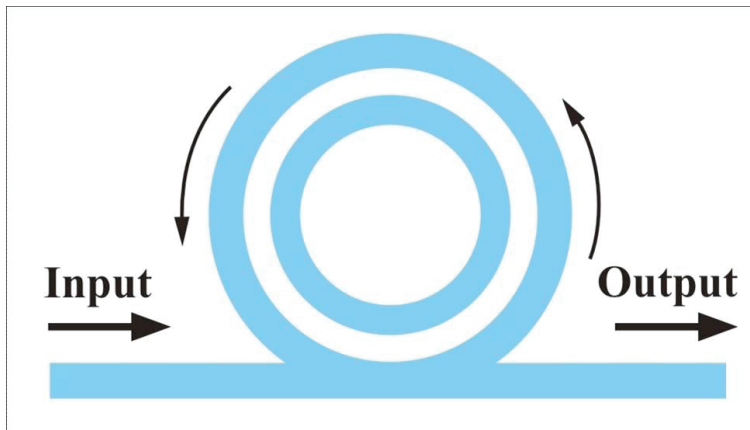


Fig. 1. A schematic diagram of the double nano-ring resonator.

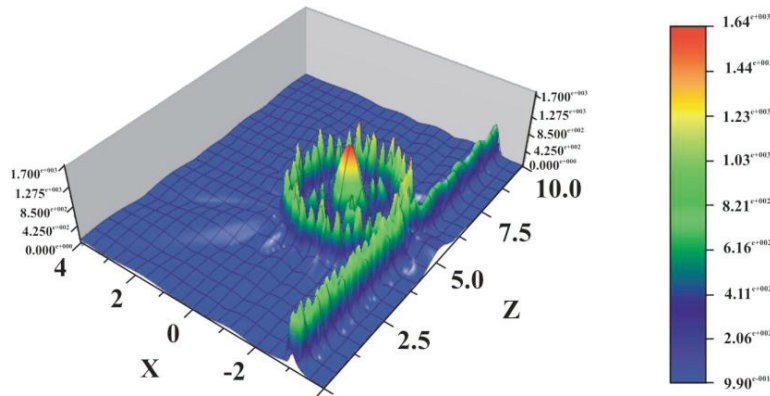


Fig. 2. Leaky light mode in the double nano-ring resonator, with the inner ring radius of $0.775 \mu\text{m}$, the outer ring radius of $1.55 \mu\text{m}$ (maximum center peak intensity).

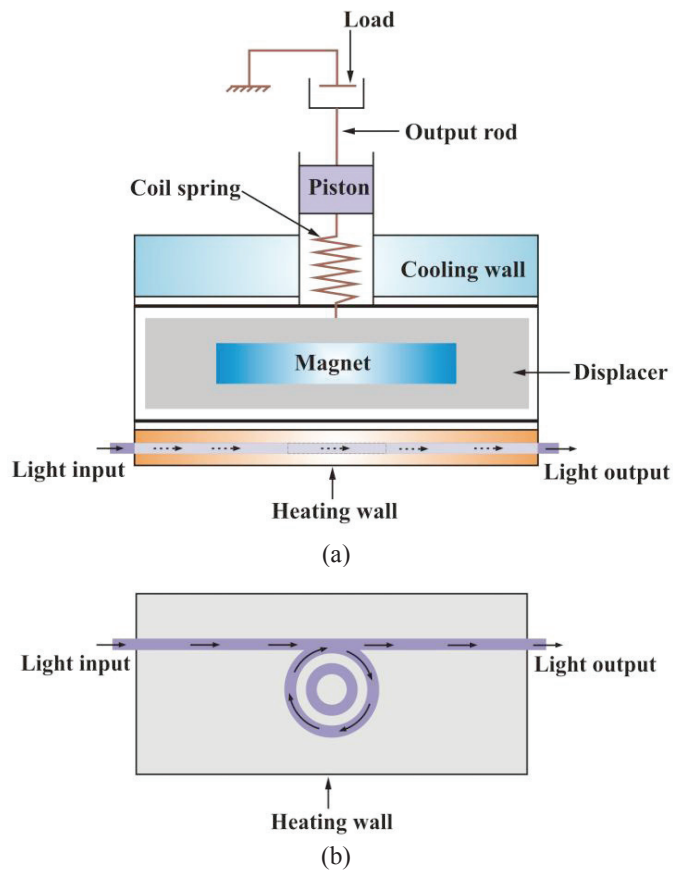


Fig.3 (a) a schematic of micro-Stirling engine using a nano-heat source, (b) heat source (nano-ring resonator)

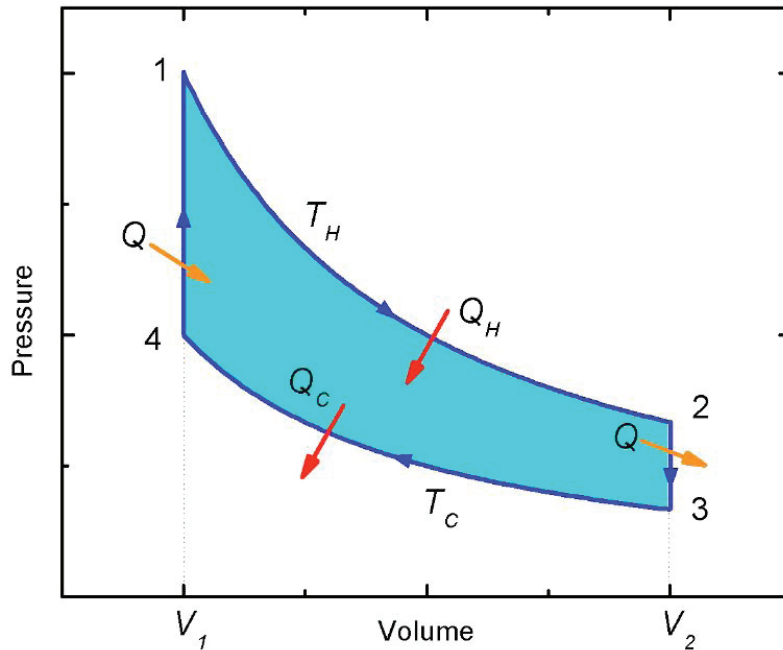


Fig-4. The idealized Stirling engine cycle

Fig. 3 [31] shows the concept of the micro-Stirling engine. The piston and the displacer are mechanically connected with a spring. A small magnet is situated inside the displacer, and the heating wall and the cooling wall are made of mild steel. Liquid nitrogen contained in cooling wall. The spring and the magnet comprise as a snap action mechanism, which maintains phase difference between piston and displacer, sustaining the reciprocating movement even at relatively low frequency. The idealized Stirling cycle consists of four thermodynamic processes acting on the working fluid as shown in Fig. 4, where, (1) Isothermal Expansion, where the expansion-space and associated heat exchanger are maintained at a constant high temperature, and the gas undergoes near-isothermal expansion absorbing heat from the hot source (high intensity peak of leaky light mode), (2) Constant-Volume (known as isovolumetric or isochoric) heat-removal, the gas is passed through the regenerator, where it cools transferring heat to the regenerator for use in the next cycle, (3) Isothermal Compression, where the compression space and associated heat exchanger are maintained at a constant low temperature so the gas undergoes near-isothermal compression rejecting heat to the cold sink (liquid nitrogen), and (4) Constant-Volume (known as isovolumetric or isochoric) heat-addition, where the gas passes back through the regenerator where it recovers much of the heat transferred in 2, heating up on its way to the expansion space.

3. Conclusion

The WGMs in nanoring resonator could be occurred if the ring radius is satisfied the specific condition, which can be controlled or amplified by varying the ring radii. According to the simulation results we can apply the high intensity whispering gallery modes for micro-Stirling engine operation by the integrated optic system, in which the performance of micro-Stirling engine can be controlled by laser or ring parameter control.

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